

Constraints on sub-GeV hidden sector gauge bosons from a search for heavy neutrino decays

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Abstract

Several models of dark matter motivate the concept of hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. The interaction between our and hidden matter could be transmitted by new abelian $U'(1)$ gauge bosons A' mixing with ordinary photons. If such A' 's with the mass in the sub-GeV range exist, they would be produced through mixing with photons emitted in decays of η and η' neutral mesons generated by the high energy proton beam in a neutrino target. The A' 's would then penetrate the downstream shielding and be observed in a neutrino detector via their $A' \rightarrow e^+e^-$ decays. Using bounds from the CHARM neutrino experiment at CERN that searched for an excess of e^+e^- pairs from heavy neutrino decays, the area excluding the $\gamma - A'$ mixing range $10^{-7} \lesssim \epsilon \lesssim 10^{-4}$ for the A' mass region $1 \lesssim M_{A'} \lesssim 500$ MeV is derived. The obtained results are also used to constrain models, where a new gauge boson X interacts with quarks and leptons. New upper limits on the branching ratio as small as $Br(\eta \rightarrow \gamma X) \lesssim 10^{-14}$ and $Br(\eta' \rightarrow \gamma X) \lesssim 10^{-12}$ are obtained, which are several orders of magnitude more restrictive than the previous bounds from the Crystal Barrel experiment.

Key words: hidden sector photons, neutrino decay

The understanding of the origin of dark matter has great importance for cosmology and particle physics. Several interesting extensions of the Standard Model (SM) dealing with this problem suggest the existence of ‘hidden’ sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields. These sectors of particles do not interact with the ordinary matter directly and couple to it by gravity and possibly by other weak forces. For example, interaction between our and hidden matter may be transmitted by a new abelian $U'(1)$ gauge bosons A' (or hidden photons for short) mixing with ordinary photons, first discussed by Okun in his paraphoton model [1]. If the mixing strength is very weak or the mass scale of a hidden sector is too high, it is experimentally unobservable. However, in a class of models the A' may have mass and mixing

strength lying in the experimentally accessible and theoretically interesting regions. This makes further searches for A' 's interesting and attractive, for a recent review see [2], and references therein.

In the Lagrangian describing the photon-hidden photon system the only allowed connection between the hidden sector and ours is given by the kinetic mixing [1,2,3,4]

$$L_{int} = -\frac{1}{2}\epsilon F_{\mu\nu} A'^{\mu\nu} \quad (1)$$

where $F^{\mu\nu}$, $A'^{\mu\nu}$ are the ordinary and the hidden photon fields, respectively, and ϵ is their mixing strength. In the interesting case when A' has a mass, this kinetic mixing can be diagonalized resulting in a non-diagonal mass term that mixes photons with hidden-sector photons. It means any source of γ 's could produce kinematically possible massive states A' according to the appropriate mixings. Then, when the mass differences are small, photons may oscillate into hidden photons, similarly to vacuum neutrino oscillations, with a vacuum mixing angle which is precisely ϵ . If the mass differences are large, it could result in hidden photon decays, e.g. into e^+e^- pairs.

Experimental bounds on the sub-eV and sub-keV hidden photons can be obtained from searches for an electromagnetic fifth force [1,5,6], from experiments using the method of photon regeneration [7,8,9,10,11], and from stellar cooling considerations [12,13]. For example, it has been pointed out that helioscopes searching for solar axions are sensitive to the keV part of the solar spectrum of hidden photons and the CAST results [14,15] have been translated into limits on the $\gamma - A'$ mixing parameter [16,17,18,19]. Strong bounds on models with additional A' particles at a low energy scale could be obtained from astrophysical considerations [20]-[22]. However, such astrophysical constraints can be relaxed or evaded in some models, see e.g. [23]. New tests on the existence of sub-eV hidden photons at new experimental facilities, such, for example, as SHIPS [24] or IAXO [25] are in preparation.

The A' 's in the sub-GeV mass range, arising in some models, see e.g. [26,27,28,29], can be explored through the searches for $A' \rightarrow e^+e^-$ decays in beam dump experiments [30,31,32,33,34,35], or through the rare particle decays, see e.g. [36,37,38,39]. For example, if the mass of A' is below the mass of π^0 , it can be effectively searched for in the decays $\pi^0 \rightarrow \gamma A'$, with the subsequent decay of A' into e^+e^- pair. Recently, stringent constraints on the mixing ϵ in sub-GeV mass range have been obtained from a search of this decay mode with existing data of neutrino experiments [40,41,42] and from SN1987A cooling [43].

It should be noted, that many extensions of the SM such as GUTs [44], supersymmetric [45], super-string models [46] and models including a new long-range interaction, i.e. the fifth force [47], also predict an extra $U(1)$ factor and therefore the existence of a new gauge boson X corresponding to this new

group (we denote it X to distinguish from A'). The X 's could interact directly with quarks and/or leptons, and although the predictions for its mass are not very firm it could be light enough ($M_X \ll M_Z$) for searches at low energies. If the mass M_X is in the sub-GeV range, i.e. of the order of the pion mass, an effective search could be conducted for this new vector boson in the radiative decays of neutral pseudoscalar mesons $P \rightarrow \gamma X$, where $P = \pi^0, \eta$, or η' , because the decay rate of $P \rightarrow \gamma + \text{any new particles with spin 0 or } \frac{1}{2}$ proves to be negligibly small [48]. Therefore, a positive result in the direct search for these decay modes could be interpreted unambiguously as the discovery of a new light spin 1 particle, in contrast with other experiments searching for light weakly interacting particles in rare K , π or μ decays [48,49,50].

Stringent limits on the decay $\pi^0 \rightarrow \gamma A'(X)$, $A'(X) \rightarrow e^+e^-$, obtained by using results from neutrino experiments have been recently reported in Ref. [40]. The best experimental limits on the branching ratio of the decay $\eta(\eta') \rightarrow \gamma X$ were obtained by the Crystal Barrel Collaboration at CERN [51,52]. Using proton-antiproton annihilation as a source of X 's from $\eta(\eta') \rightarrow \gamma X$ decays, they searched for the corresponding γ -peak in their detector, resulting in 90 % C.L. upper limits on the branching ratio $Br(\eta \rightarrow \gamma X) < 6 \times 10^{-5}$ for M_X masses ranging from 200 to 525 MeV, and $Br(\eta' \rightarrow \gamma X) < 4 \times 10^{-5}$ for M_X between 50 MeV and 925 MeV [51,52]. The goal of this Letter is to show that more stringent limits on the decay $\eta(\eta') \rightarrow \gamma A'(X)$, followed by the decay $A'(X) \rightarrow e^+e^-$, and the mixing ϵ for A' masses up to $\simeq 500$ MeV can be obtained from the results of sensitive searches for an excess of single isolated e^+e^- pairs from decays of heavy neutrinos in the sub-GeV mass range by the CHARM experiment at CERN [53,54].

The CHARM Collaboration searched for decays $\nu_h \rightarrow \nu e^+e^-$ of heavy neutrinos in the ν_h mass range from 10 MeV to 1.8 GeV originated from decays π , K and charmed D mesons decays [53,54]. The experiment, specifically designed to search for neutrino decays in a high-energy neutrino beam, was performed by using 400 GeV protons from the CERN Super Proton Synchrotron (SPS) with the total number of 2.4×10^{18} protons on (Cu) target (pot). The CHARM decay detector (DD), located at the distance of 480 m from the target, consist of decay volume of $3 \times 3 \times 35 \text{ m}^3$, three chambers modules located inside the volume to detect charged tracks and followed by a calorimeter. The decay volume was essentially an empty region to substantially reduced the number of ordinary neutrino interactions. The signature of the heavy neutrino decay $\nu_h \rightarrow \nu e^+e^-$ were events originating in the decay region at a small angle with respect to the neutrino beam axis with one or two separate electromagnetic showers in the calorimeter [54]. No such events were observed and limits were established on the $\nu_{e,\mu} - \nu_h$ mixing strength as a function of the ν_h mass. If the decays $\eta, \eta' \rightarrow \gamma A'$ exist, one expects a flux of high energy A' 's from the SPS target, since neutral mesons η and η' are abundantly produced in the forward direction by high energy protons in the target. If A' is a relatively

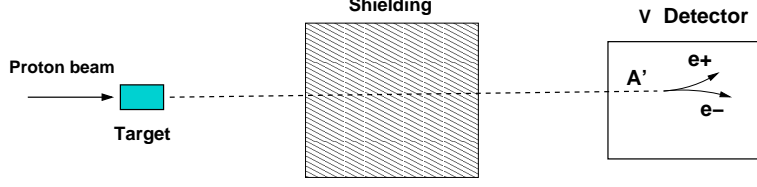


Fig. 1. *Schematic illustration of a proton beam dump experiment on search for $P \rightarrow \gamma A'$, $A' \rightarrow e^+e^-$ decay chain: neutral mesons P generated by the proton beam in the target produce a flux of high energy A' 's through the $\gamma - A'$ mixing in the decay $P \rightarrow \gamma\gamma$, which penetrate the downstream shielding and decay into e^+e^- pair in a neutrino detector. The same setup can be used to search for the process $P \rightarrow \gamma X$, $X \rightarrow e^+e^-$. See text.*

long-lived particle, this flux would penetrate the downstream shielding without significant attenuation and would be observed in the CHARM detector via the $A' \rightarrow e^+e^-$ decay into a high energy e^+e^- pair, as schematically illustrated in Fig. 1. The occurrence of $A' \rightarrow e^+e^-$ decays would appear as an excess of e^+e^- pairs in the CHARM DD above those expected from standard neutrino interactions. The experimental signature of these events is clean and they can be selected in the CHARM DD with a small background. As the final states of the decays $\nu_h \rightarrow \nu e^+e^-$ and $A' \rightarrow e^+e^-$ are identical, the results of the searches for the former can be used to constrain the later for the same e^+e^- invariant mass regions.

The flux of hidden photons from decays of η 's and η' 's produced in the target by primary protons can be expressed as follows:

$$\Phi(A') \propto N_{pot} \int \frac{d^3\sigma(p + N \rightarrow \eta(\eta') + X)}{d^3p_{\eta(\eta')}} \epsilon^2 Br(\eta(\eta') \rightarrow \gamma\gamma) f d^3p_{\eta(\eta')} \quad (2)$$

where N_{pot} is the number of pot, $\sigma(p + N \rightarrow \eta(\eta') + X)$ is the $\eta(\eta')$ meson production cross-section, $Br(\eta(\eta') \rightarrow \gamma\gamma)$ is the $\eta(\eta') \rightarrow 2\gamma$ decay mode branching fraction [55], and f is the decay phase space factor, respectively.

To perform calculations we used simulations of the process shown in Fig.1 from our previous work on $\pi^0 \rightarrow \gamma A'$ decays [40] by taken into account the relative normalization of the yield of different meson species $\pi^0 : \eta : \eta'$ from the original publications. The invariant cross section of a hadron production can be expressed as [55]

$$E \frac{d^3\sigma}{d^3p} = \frac{d^3\sigma}{p_T dp_T dy d\phi} = \frac{d^2\sigma}{2\pi p_T dp_T dy} \quad (3)$$

where p_T is the transverse momentum of the particle, y is its rapidity, and in the last equality integration over the full 2π azimuthal angle ϕ is performed. For the production cross sections of η and η' neutral mesons we used the Bourquin-Gaillard (B-G) formula from Ref.[56], which gives the parametric

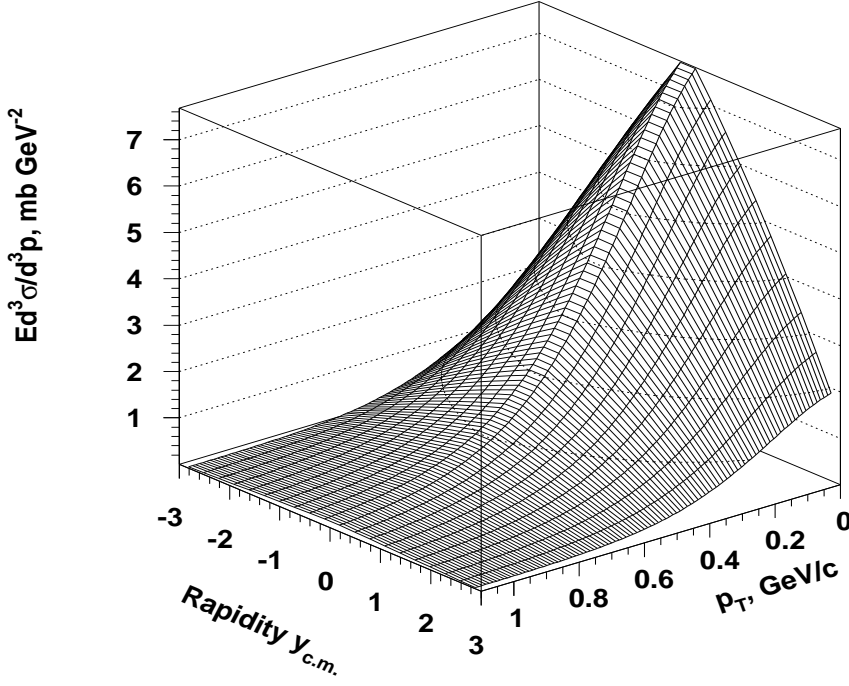


Fig. 2. Invariant cross section for η production in pp collisions at $\sqrt{s} = 27.4$ GeV vs p_T and rapidity $y_{c.m.}$ over the range $-3.0 < y_{c.m.} < 3.0$.

form of (3) for the production in high-energy hadronic collisions of many different hadrons over the full phase-space:

$$E \frac{d^3\sigma(p + N \rightarrow \eta(\eta') + X)}{d^3p} = A_{\eta(\eta')} \left(\frac{2}{E_T + 2} \right)^{12.3} \exp\left(-\frac{5.13}{Y^{0.38}}\right) f(p_T), \quad (4)$$

where

$$f(p_T) = \begin{cases} \exp(-p_T) & p_T < 1 \text{ GeV}/c \\ \exp(-1 - 23(p_T - 1)/\sqrt{s}) & p_T > 1 \text{ GeV}/c \end{cases}$$

with $Y = y_{max} - y$, being the rapidity, and $E_T(p_T)$ the transverse energy (momentum) in GeV. Coefficients $A_{\eta(\eta')}$ in (4) are normalization factors that were tuned to obtain the cross sections σ_η and $\sigma_{\eta'}$ in pp collisions at 400 GeV/c. In these calculations for the relative yields of $\pi^0 : \eta : \eta'$ mesons the values $1 : 0.078 : 0.024$, respectively, were used, which were obtained from the measurements of the total cross sections $\sigma_{\pi^0}(127.2 \pm 1.5 \pm 3.2 \text{ mb})$ and $\sigma_\eta(9.78 \pm 0.56 \text{ mb})$, and from an estimate of the η' production in pp -interactions at 400 GeV/c by the NA27 experiment at CERN SPS [57]. The invariant η production cross section, obtained by using the B-G parameterization (4), is shown in Fig. 2 as a function of p_T and rapidity $y_{c.m.}$ in the center of mass system. The total η and η' production cross sections in p-Cu collisions were calculated from its linear extrapolation to the target atomic number. The B-

G p_T distributions at low transverse momenta were corrected by taking into account the measurements results of π^0 's and η 's production in 450 GeV p-Be and p-Au collisions down to very low p_T ($\gtrsim 20$ MeV/c) obtained by a joint experiment of the TAPS and CERES Collaborations at the CERN SPS [58]. In this experiment precise measurement data on η -production at low p_T , revealed a lower cross section than expected from extrapolating data at higher p_T . The B-G parameterization, found to be in a good agreement with π^0 data for the full p_T range, and also with the η data for the large ($p_T \gtrsim 0.4$ GeV/c) momentum transfer, overestimates the production rate of η mesons by 25-30% at transverse momenta $p_T \lesssim 0.4$ GeV/c. This observation results in decrease of the acceptance of the CHARM DD for A' 's produced in $\eta(\eta') \rightarrow \gamma A'$ decays and, hence has to be taken into account. To achieve a better description of the low- p_T -region, a parameterization suggested by [58,59] was used:

$$E \frac{d^3\sigma}{d^3p} = B_{\eta(\eta')} \left(\beta \exp(-bm_T) + \alpha \frac{(1-x_T)^c}{(1+m_T^2)^4} \right) \quad (5)$$

where m_T is the transverse mass, $x_T = 2m_T/\sqrt{s}$, and parameters $\beta = 0.15$, $b = 6.5$ GeV $^{-1}$, $\alpha = 0.011$, $c = 7.9$ and normalization factors $B_{\eta(\eta')}$ were determined in Ref.[58] by fitting the precise low p_T experimental data in the rapidity range $3 < y < 4$. The results of fitting were also in good agreement with other meson production data obtained for different rapidity intervals. The comparison of two parameterizations is shown in Fig. 3. We used Eq.(5) also for calculations of low p_T distributions of η' mesons.

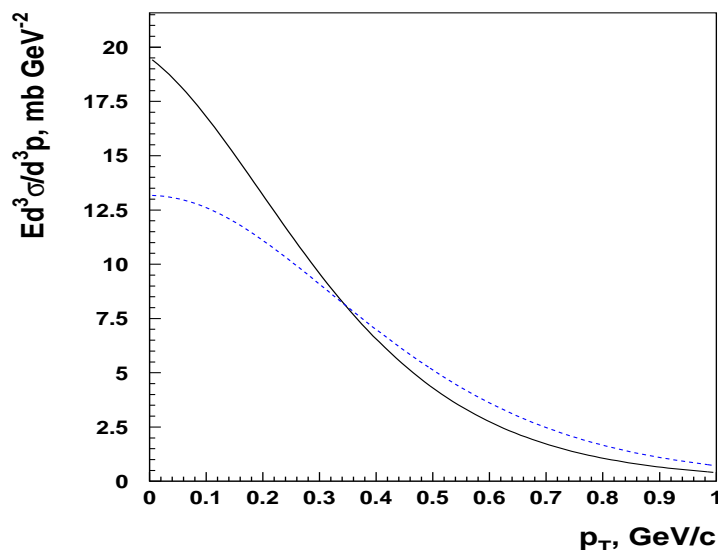


Fig. 3. Invariant cross section for η mesons production in pp collisions at $\sqrt{s} = 27.4$ GeV calculated as a function of p_T in the low- p_T region for the B-G parameterization of Eq.(4) (solid curve), and from Eq.(5) (dashed curve).

The calculated fluxes and energy distributions of η, η' produced in the Cu target were used to predict the flux of A' 's, as a function of its mass. For a given flux $d\Phi(M_{A'}, E_{A'}, N_{pot})/dE_{A'}$ of A' 's the expected number of $A' \rightarrow e^+e^-$ decays occurring within the fiducial length L of the CHARM detector located at a distance L' from the neutrino target is given by

$$N_{A' \rightarrow e^+e^-} = Br(\eta(\eta') \rightarrow \gamma A') Br(A' \rightarrow e^+e^-) \int \frac{d\Phi}{dE_{A'}} \cdot \exp\left(-\frac{L' M_{A'}}{P_{A'} \tau_{A'}}\right) \left[1 - \exp\left(-\frac{L M_{A'}}{P_{A'} \tau_{A'}}\right)\right] \zeta A dE_{A'} \quad (6)$$

where $E_{A'}$, $P_{A'}$, and $\tau_{A'}$ are the A' energy, momentum and the lifetime at rest, respectively, and ζ is the e^+e^- pair reconstruction efficiency. The acceptance A of the DD was calculated tracing A' 's produced in the Cu-target to the detector taking the relevant momentum and angular distributions into account. As an example for a mass $M_{A'} = 300$ MeV, $A = 0.07$ and $\zeta \simeq 0.6$ [53]. In this estimate the average momentum is $\langle p_{A'} \rangle \simeq 35$ GeV and $L \simeq 10$ m.

The obtained results can be used to impose constraints on the previously discussed models with A' hidden photons. For A' masses below the mass $M_{\eta(\eta')}$ of $\eta(\eta')$ meson, the corresponding branching fraction of the decay $\eta(\eta') \rightarrow \gamma A'$, is given by [26,27]:

$$Br(\eta \rightarrow \gamma A') = 2\epsilon^2 Br(\eta \rightarrow \gamma\gamma) \left(1 - \frac{M_{A'}^2}{M_\eta^2}\right)^3 \quad (7)$$

with the similar expression for the η' decay. Assuming the dominant A' boson decay is into e^+e^- results in a corresponding decay rate, which for small mixing is given by:

$$\Gamma(A' \rightarrow e^+e^-) = \frac{\alpha}{3} \epsilon^2 M_{A'} \sqrt{1 - \frac{4m_e^2}{M_{A'}^2}} \left(1 + \frac{2m_e^2}{M_{A'}^2}\right) \quad (8)$$

Using the relation $N_{e^+e^-}^{90\%} > N_{A' \rightarrow e^+e^-}$, where $N_{e^+e^-}^{90\%}$ ($= 2.3$ events) is the 90% *C.L.* upper limit for the number of signal events [53,54] and Eqs.(7,8), one can determine the 90% *C.L.* exclusion region in the $(M_{A'}, \epsilon)$ plane from the results of the CHARM experiment, which is shown in Fig. 4 together with regions excluded by the Nomad [40] and electron beam dump experiments E137, E141, E774 [30,31,33,34], and by recent measurements from APEX [35], KLOE [36], BaBar [38] and MAMI [39].

The shape of the exclusion contour from the CHARM experiment corresponding to the A' mass range $M_{A'} \gtrsim 300$ MeV is defined mainly by the phase space factor in (7). Using similar considerations the exclusion area for the

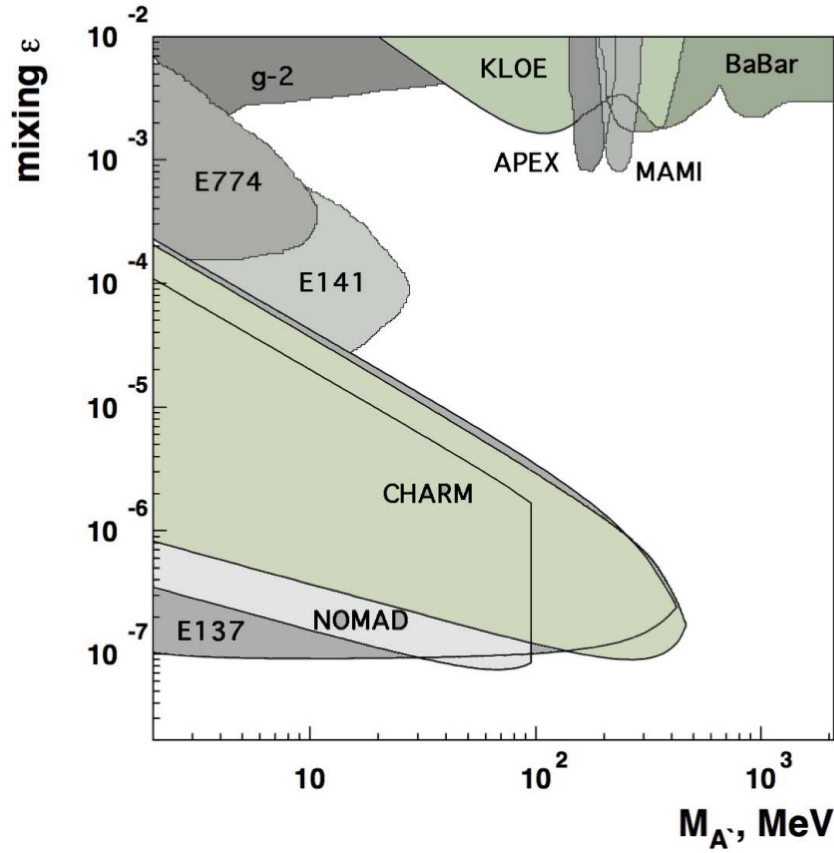


Fig. 4. Exclusion region in the $(M_{A'}, \epsilon)$ plane obtained in the present work from the results of the CHARM experiment [53,54]. The areas excluded from the $(g-2)$ considerations, the results of the Nomad [40] and electron beam dump experiments E137 [30,31], E141 [33], E774 [34], and from the searches by APEX [35], KLOE[36], BaBar[38] and MAMI [39] are also shown for comparison.

decay $\eta' \rightarrow \gamma A'$ has been also obtained. However, due to the lower η' production cross section and a small branching fraction of the decay $\eta' \rightarrow \gamma\gamma$ this exclusion area falls basically within that of obtained for η decays. Note, that the uncertainty for the η production at low p_T does not significantly affect the limits derived. For example, the variation of the η yield in (6) by 25% results in the corresponding variation of the limits on mixing strength ϵ of the order of 5%. This is because the sensitivity of the search is proportional to the ϵ^4 . Indeed, in (6) the branching fraction of (7) and the decay rate $\Gamma(A' \rightarrow e^+e^-)$ of (8) both are proportional to ϵ^2 .

We can also constrain models where the previously discussed X bosons interact with both quarks and leptons. The 90% *C.L.* upper limits on the $Br(\eta(\eta') \rightarrow \gamma X)Br(X \rightarrow e^+e^-)$ vs X lifetime τ_X shown in Fig. 5 were calculated by using the relation $N_{e^+e^-}^{90\%} > N_{X \rightarrow e^+e^-}$ and Eq.(6). Our result is sensitive to a

branching ratio $Br(\eta(\eta') \rightarrow \gamma X) \gtrsim 10^{-14}(10^{-12})$, which is about nine (eight) orders of magnitude smaller than the previous limit from the Crystal Barrel experiment[51,52]. Over most of the τ_X region, the X lifetime is sufficiently long, that $LM_X/p_X\tau_X \ll L'M_X/p_X\tau_X \ll 1$. The interaction of X bosons with

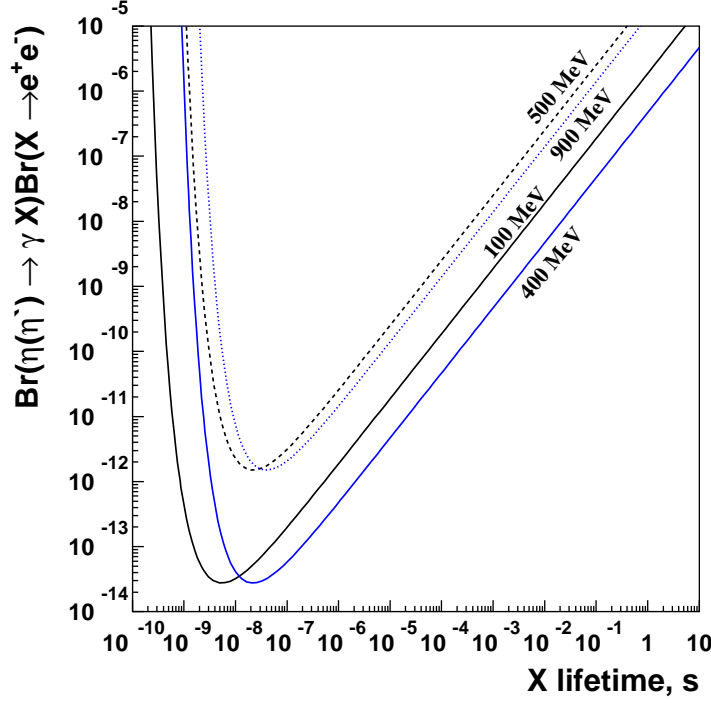


Fig. 5. The 90% C.L. upper limits on the branching ratio $Br(\eta(\eta') \rightarrow \gamma X)Br(X \rightarrow e^+e^-)$ versus τ_X obtained from the CHARM experiment for η (solid curves) and η' (dashed curves) decays. The numbers near the curves indicate the corresponding values of M_X .

both quarks and leptons can be written in the form:

$$L_X = g_X(Q_{BX}B^i + Q_{eX}L_e^i + Q_{\mu X}L_\mu^i + Q_{\tau X}L_\tau^i)X^i \quad (9)$$

where $\alpha_X = g_X^2/4\pi$ is the coupling constant, $B^i = \sum_{q=u,d,s,\dots} \bar{q}\gamma^i q$, $L_e^i = \bar{e}\gamma^i e + \bar{\nu}_{eL}\gamma^i \nu_{eL}$, ..., see e.g. [48,50]. Assuming charges $Q_{BX} \simeq Q_{eX} \simeq 1$, we found

$$\alpha_X < k \frac{1}{M_X [\text{MeV}]} \left(1 - \frac{M_X^2}{M_\eta^2}\right)^{-3/2}, \quad (10)$$

which is valid for $k = 4.3 \times 10^{-12}$ and $M_X < 2M_\pi$ (270 MeV). For the mass range from 270 to M_η (548 MeV) the decay channel $X \rightarrow \pi\pi$ is open. To calculate this decay rate is not a simple task, because the QCD long distance effects have to be taken into account [49]. Therefore, to avoid this difficulty, we used for this decay rate a reasonable estimate $\Gamma(X \rightarrow \pi\pi) \simeq \alpha_X Q_{BX}^2 M_X$,

which results in $k = 1.4 \times 10^{-12}$ for $Q_{BX} \simeq 1$. From the similar considerations, for the mass range $M_\eta < M_X < M_{\eta'} (948 \text{ MeV})$ the limit on the coupling constant is given by (10) with replacements $k = 3.5 \times 10^{-10}$ and $M_{\eta'}$ instead of M_η . The bounds (10) are valid for $\tau_X \gtrsim 10^{-10} M_X [\text{MeV}] \text{ s}$. They are more restrictive than those obtained in [49,50], and than bounds reported by NOMAD [42]. Less stringent limits (by a factor $\simeq \alpha$) could be obtained for the cases where the X interacts only with leptons, or when it is a leptophobic boson which interacts only with quarks and decays into e^+e^- pair through the quark loop [49,50]. For X produced in η decay with the masses $M_X < 545 \text{ MeV}/c^2$ the best limits from CHARM are in the region $Br(\eta \rightarrow \gamma X) Br(X \rightarrow e^+e^-) \lesssim (2 - 3) \times 10^{-14}$, while the corresponding limits for X 's with masses $M_X < 948 \text{ MeV}/c^2$ from η' decays are $Br(\eta' \rightarrow \gamma X) Br(X \rightarrow e^+e^-) \lesssim 2 \times 10^{-12}$. The attenuation of the X - flux due to X interactions with matter was found to be negligible, e.g. for couplings of (10) the X boson mean free path in iron is much longer, as compared with the iron and earth shielding total length of 0.4 km used for the CHARM beam.

In summary, using sensitive limits from the CHARM experiments on heavy neutrino decays $\nu_h \rightarrow \nu e^+e^-$, new bounds on a hidden sector gauge A' bosons produced in the neutral meson decay $\eta(\eta') \rightarrow \gamma A'$ in the sub-GeV A' mass range are obtained. The A' 's could mediate interaction between our world and hidden sectors consisting of $SU(3)_C \times SU(2)_L \times U(1)_Y$ singlet fields through the mixing with ordinary photons. For the A' mass region $1 \lesssim M_{A'} \lesssim 500 \text{ MeV}$ the obtained exclusion area covers the $\gamma - A'$ mixing strength in the range $10^{-7} \lesssim \epsilon \lesssim 10^{-4}$. The results obtained are also applicable to the η and η' decays into a photon and a new gauge bosons X that interacts with quarks and leptons, or only with quarks. Our best result is sensitive to a branching ratio $Br(\eta(\eta') \rightarrow \gamma X) \gtrsim 10^{-14} (10^{-12})$, which is about nine (eight) orders of magnitude stronger than the previous limit from the Crystal Ball experiment [51,52]. The obtained constraints were used to set new limits on the X coupling strength to lepton and quarks which are more restrictive than bounds from previous searches. These results enhance existing motivations for further more sensitive search for $A'(X)$ decay at the high intensity frontier [60] and additional tests of hidden sectors in neutrino experiments.

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